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Short communication

Controllable fuel cell humidification by ultrasonic atomization

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HIGHLIGHTS

- An ultrasonic atomizer was designed to improve the efficiency for PEMFC.
- The atomizer can adjust the relative humidity to improve the fuel cell performance.
- The RH values can reach or exceed 90% for both air and hydrogen given optimal parameter settings.
- Compared to a bubble type humidifier, the atomizer can actively increase the humidity.

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ABSTRACT

Compared with the conventional bubble-type humidifier used for PEMFC (proton exchange membrane fuel cell) humidification, ultrasonic atomization has the advantages of a small size, ease in refilling and changing temperature, and more importantly, controllable humidity. This study develops a unique ultrasonic atomization system that includes a gas heating pipe, an ultrasonic driving circuit, an ultrasonic atomizer, and humidity sensors. The reactive gases used are hydrogen and air. The gas humidity increases due to the ultrasonic micro water droplets that blend with the gases. The humidity is controlled by adjusting either the heating temperature or the driving voltage. In addition, the size of the micro water droplets can be manipulated by adjusting the driving frequency. An increased driving frequency leads to a smaller mean droplet diameter, which increases the humidification efficiency. A relative humidity of at least 90% can be maintained for gas flow rates between 1 and 25 LPM. The conventional bubble-type humidification can achieve only ~80% relative humidity under the same conditions. The I–V curve also indicates that an optimal humidity is required for improved performance. Thus, a dynamic controllability of the humidification is important, especially for high-capacity FC (fuel cell) performance.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are considered potential energy sources for automobile power and residential applications given their advantages over other fuel cells in terms of rapid start-up, high power density, low operating temperature, and immediate response to changes in the demand for power. However, PEMFCs require that high water content be maintained in the electrolyte to ensure high ionic conductivity. Therefore, the membrane must be fully humidified to offer a low resistance to the current flow and to increase the overall efficiency of the PEMFC [1,2].

Three methods for humidification have traditionally been employed: Bubble-type humidification is the most commonly used method in which the dry reactive gases are pumped directly into hot water and humidified after absorbing its thermal energy. Because the humidity is controlled by the temperature of the water, this method cannot easily control the humidity. Therefore, although this method is inexpensive and easy to operate, it is a relatively passive method. Because Teflon is breathable and waterproof, a membrane made of a thin Teflon film is also commonly used for humidification. Hot water passes over one side of a thin Teflon film, and the dry reactive gas passes over the other side. However, after long periods of operation, the pores of the Teflon film become blocked by impurities in the water, reducing the moisture exchange. In addition to these two methods, steam injection also provides an efficient humidification technique, utilizing a nebulizer to produce an intensive spray into an enthalpy mixer. The dry reactive gas is humidified when combined with the sprayed vapor. However, the humidification is discontinuous because the nebulizer is unable to produce a continuous spray.

Ultrasonic waves were first proposed for generating vapor sprays by Wood and Loomis in early 1927 [3]. They observed that a thin liquid layer could be atomized on a Langevin-type vibrator operating at 300 kHz. When a high-intensity ultrasonic wave

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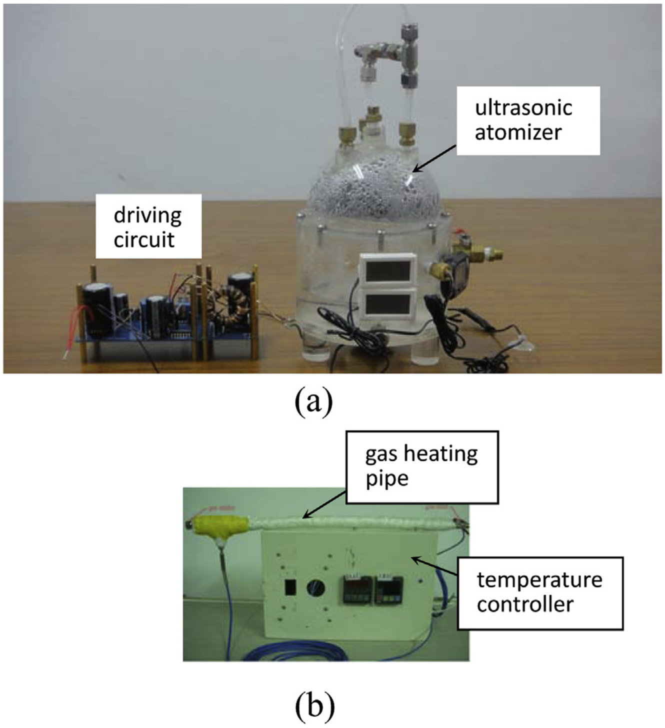

Fig. 1. Homemade ultrasonic atomization system (a) driving circuit and ultrasonic atomizer (b) gas heating pipe.

vibrates a liquid, small droplets can be excited from the surface of the liquid, a phenomenon called ultrasonic atomization. Ultrasonic atomization induced by a shock vibration from a piezoelectric crystal film can focus the energy into an ultrasonic geyser on the surface of the liquid. Cavitation can occur in the ultrasonic geyser, and the liquid can be transformed into a vapor bubble after vibration. The pressure in the bubble is quite unstable, and the diameter of the bubble increases with its internal pressure. When the pressure of the bubble reaches a critical value, it will eventually collapse. Then, the bubble is transferred to an intensive spray, achieving ultrasonic atomization [4–6]. In 1871, the size of a water droplet was compared with the wavelength of capillary waves calculated using Kelvin's equation [7]. In 1962, Lang studied the relationship between drop size and excitation frequency by measuring the size of drops generated from ultrasonic vibrators excited in the range from 10 to 800 kHz [8].

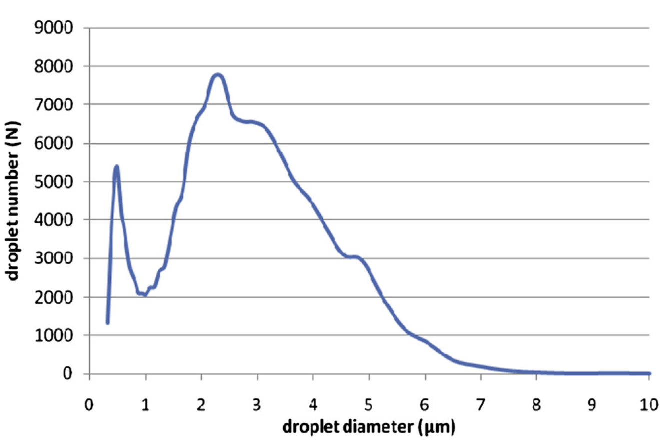

Fig. 2. The distribution of water droplet size for 2.58 MHz driving.

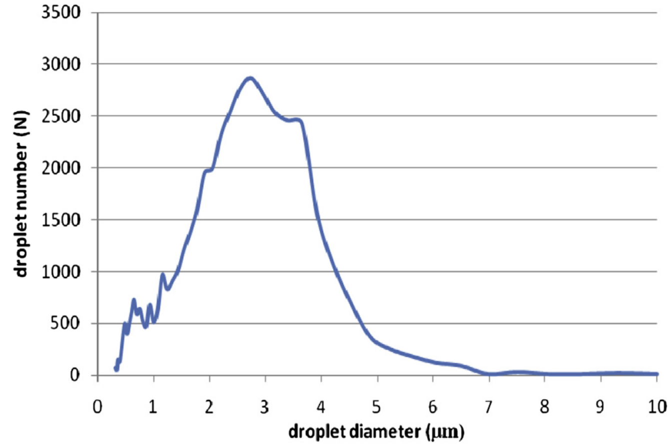

Fig. 3. The distribution of water droplet size for 1.75 MHz driving.

Because ultrasonic atomization is an efficient and controllable method for producing intensive sprays, a custom ultrasonic atomizer was used to study fuel cell humidification.

2. Experimental setup

The custom ultrasonic atomization system shown in Fig. 1 consists of a driving circuit, a gas heating pipe, an ultrasonic atomizer, thermal couples, and relative humidity (RH) sensors. The driving voltage is tunable from 30 to 150 V. The driving frequency ranges from 1.5 MHz to 2.6 MHz. The water particle size is dependent upon the driving frequency. To avoid the resonant frequencies of the piezo transducer, frequencies of 1.75 MHz and

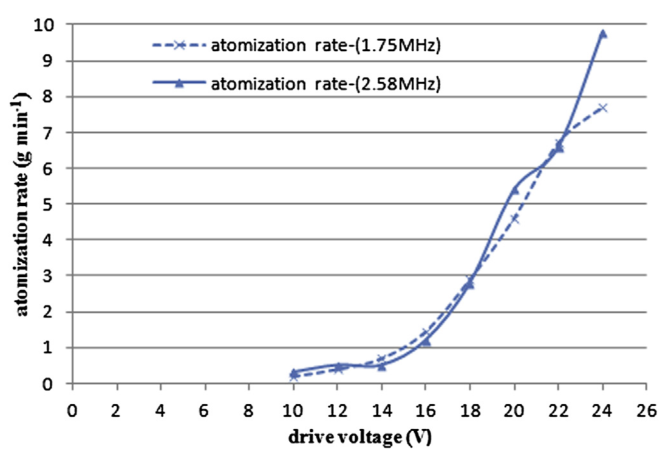

Fig. 4. The atomization rate for various driving voltage.

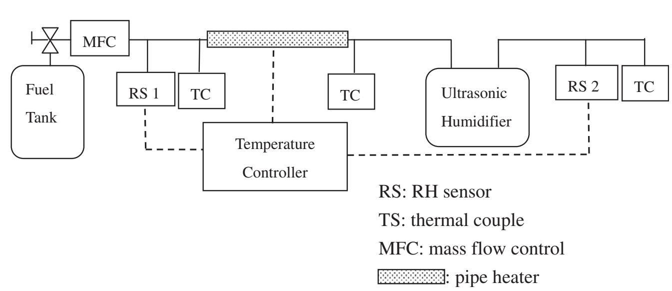

Fig. 5. The setup for the humidity measurement.

Table 1
Test conditions for air and hydrogen humidification by bubble type.

Parameters	Value
Water temperature, °C	40
Flow rate, LPM	1–25
RS2 temperature, °C	40

Table 2
Parameter setting for air and hydrogen humidification by ultrasonic atomization.

Parameters	Experiment 1	Experiment 2	Experiment 3
Flow rate, LPM	1–25	15/10	15/10
Driving voltage, V	18	12–24	18
Gas inlet temperature, °C	90	90	60–100
RS2 temperature, °C	40	40	40
Driving frequency, MHz	1.75 & 2.58	1.75 & 2.58	1.75 & 2.58
Humidified gas (cathode/anode)	Air/H_2	Air/H_2	Air/H_2

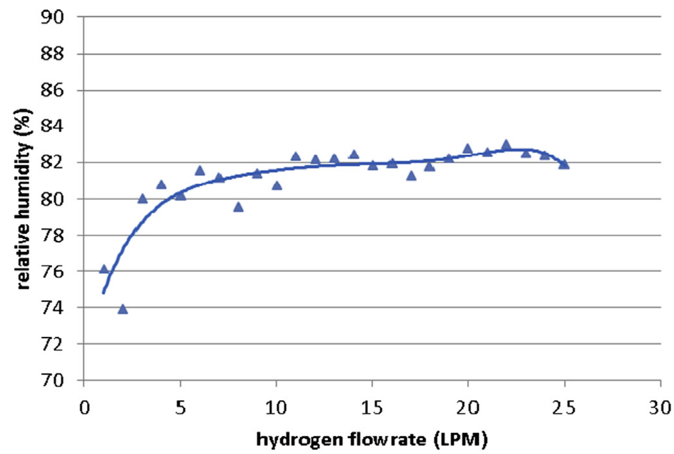

Fig. 7. Bubble type humidification for hydrogen.

2.58 MHz were chosen, and the corresponding average particle sizes—as measured using a Palas Welas 3000—were 2.2 mm and 1.9 mm, respectively (Palas GmbH, Greschbachstrasse 3 b, 76229 Karlsruhe, Germany) (Figs. 2 and 3). The atomization rate can be increased by increasing the driving voltage (Fig. 4), producing atomization rates of 7.7 g min^{-1} and 9.8 g min^{-1} at 1.75 MHz and 2.58 MHz, respectively, for a 24-V driving voltage.

After absorbing enough thermal energy from the gas heating pipe (Fig. 1(b)), the dry gas flows into the 1-L ultrasonic atomizer (Fig. 1(a)). The liquid water mist generated inside the ultrasonic atomizer is converted into water vapor via heat exchange and is carried away by the incoming gas. The gas is humidified, and the humidity can be adjusted by either tuning the driving voltage of the ultrasonic humidifier or by changing the temperature of the heater.

Fig. 5 shows the apparatus for measuring the humidity. The relative humidity sensor RH1 measures the relative humidity of the unhumidified (dry) gas from the fuel tank. The relative humidity sensor RH2 measures the relative humidity of the humidified gas from the ultrasonic humidifier outlet. The temperatures of the RH sensors and the gas heater are controlled using the temperature controller.

A traditional bubble-type humidifier with 1-L capacity was used to compare the humidification effect of an ultrasonic humidifier at various gas flow rates. The test conditions for the humidification of air and hydrogen using a bubble-type humidifier are provided in Table 1. A variety of parameters (gas flow rate, driving voltage, gas temperature, and driving frequency) can affect the performance of the ultrasonic humidifier. Table 2 shows the parameter settings of the ultrasonic atomizer.

3. Results and discussion

Figs. 6 and 7 present the results of the bubble-type humidification for air and hydrogen, respectively, at the test conditions given in Table 1. In Fig. 6, the relative humidity of the air is approximately 75% for the lower flow rates and increases to a maximum of 85% when the flow rate reaches 11 LPM. Then, the relative humidity decreases with the increasing flow rate to reach 78% for 25 LPM. In Fig. 7, the relative humidity of hydrogen is also approximately 75% at the lower flow rates and increases to approximately 81–83% above 3 LPM. For both air and hydrogen gas, the humidity can be varied by varying the water temperature; however, the processes are relatively undynamic and inefficient, especially at high flow rates, due to the large quantities of water that must be heated.

Using the parameters set for Experiment 1 in Table 2, the reactive gases were humidified by the ultrasonic atomizer. Fig. 8 provides the results of the ultrasonic humidification for air. The RH is approximately 91–92% for a flow rate of 2 LPM and increases to above 95% when the flow rate is between 4 and 10 LPM. However, the RH decreases to less than 90% with a flow rate of 15 LPM and to 84% at 25 LPM. Fig. 9 provides the ultrasonic humidification results for hydrogen. The general trend of the hydrogen humidification is similar to that of air, but the RH value is lower, reaching approximately 92% at 8 LPM, decreasing to less than 90% at 10 LPM,

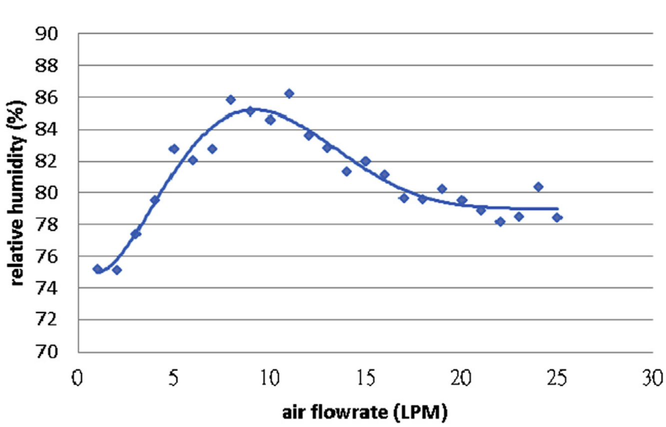

Fig. 6. Bubble type humidification for air.

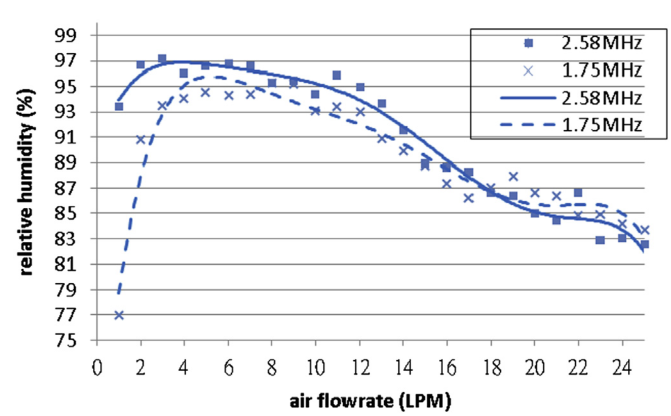

Fig. 8. Ultrasonic humidification for air.

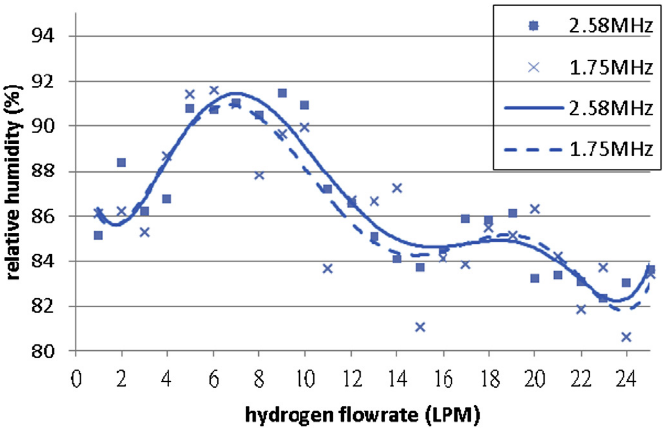

Fig. 9. Ultrasonic humidification for hydrogen.

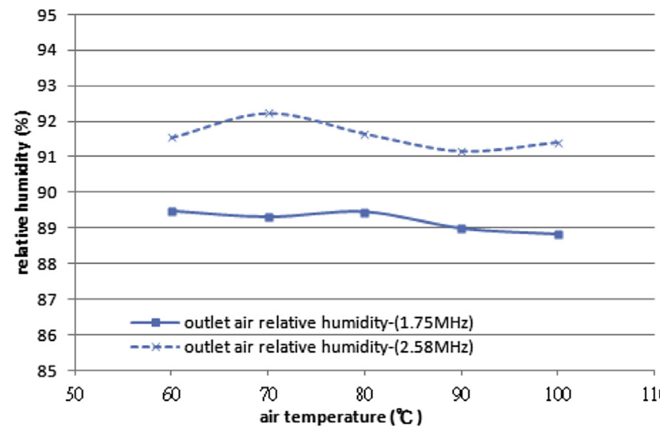

Fig. 12. Humidification for air with various inlet temperatures.

and to 82% for flow rates greater than 21 LPM. We assume that the amount of atomization driven by 18 V (Table 2) is insufficient for flow rates high enough to cause a decay of the RH value.

To verify this assumption, Experiment 2, shown in Table 2, was conducted. Figs. 10 and 11 provide the humidification results for air and hydrogen, respectively, at various driving voltages. The flow rates of 15 LPM and 10 LPM for air and hydrogen, respectively, were chosen because at those flow rates the RH value begins to decay dramatically (Figs. 8 and 9). The RH value is shown to exceed 90% with driving voltages of 22 and 24 V for air and hydrogen, respectively. A higher (2.58 MHz) driving frequency yields a higher RH value, especially at lower driving voltages (12–20 V). This result indicates that smaller water particles may enhance the humidity and that the RH value of the ultrasonic atomization is controllable and can be actively adjusted for optimal FC performance.

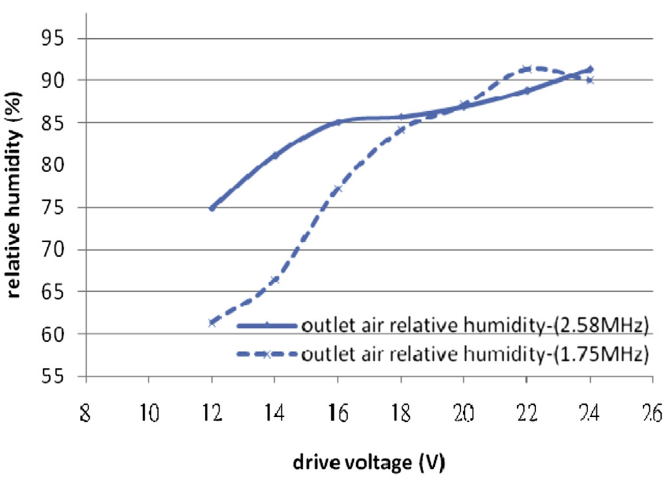

Fig. 10. Humidification for air with various driving voltages and 15 LPM flow rate.

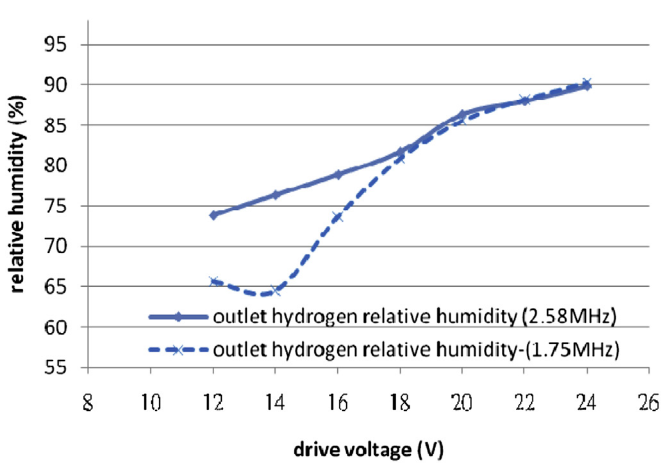

Fig. 11. Humidification for hydrogen with various driving voltages and 10 LPM flow rate.

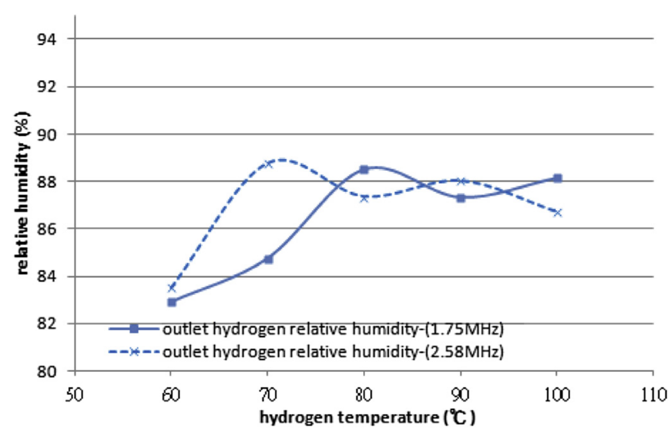

Fig. 13. Humidification for hydrogen with various inlet temperatures.

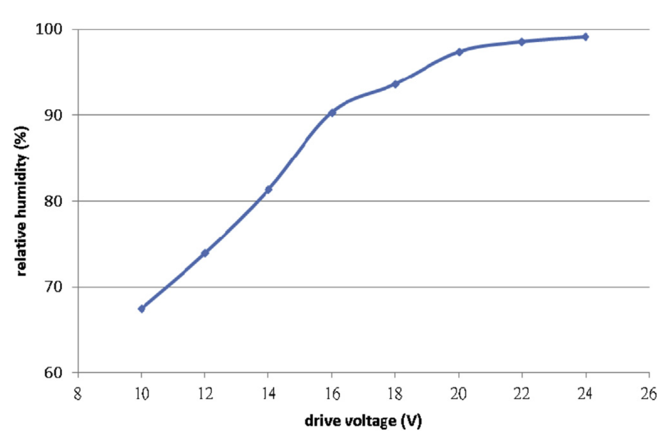

Fig. 14. Air humidity for various driving voltage at 1 LPM flow rate and 2.58 MHz driving frequency.

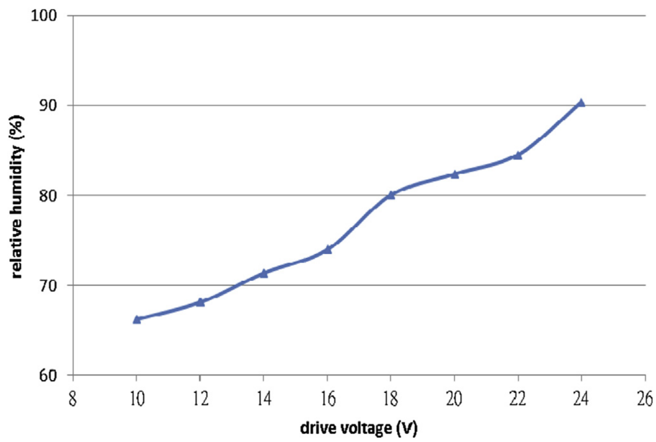

Fig. 15. Hydrogen humidity for various driving voltage at 1 LPM flow rate and 2.58 MHz driving frequency.

Because the gas temperature may also be a major factor affecting the extent of humidification, the RH values were measured using the Experiment 3 settings provided in Table 2. The RH value for air given in Fig. 12 exhibits no significant variation, remaining near 89 and 91% for driving frequencies of 1.75 and 2.58 MHz, respectively. Thus, above 60 °C, the air is energetic enough to dissolve the water droplets. In contrast, the humidification of hydrogen is relatively difficult and requires additional thermal energy (70 °C) for improved humidification (Fig. 13).

To investigate the PEMFC performance when using an ultrasonic atomizer for the anode (hydrogen) and/or cathode (air), the humidified RH values for both air and hydrogen were measured at a flow rate of 1 LPM and are shown in Figs. 14 and 15, respectively. The RH value increases with increasing driving voltage for both cases. For air (Fig. 14), the RH increases from 67% at 10 V to 97% at 20 V. For hydrogen (Fig. 15), the RH increases from 67% at 10 V to 90% at 24 V.

The performance of the PEMFC assembled in our lab was investigated by measuring the polarization (*I*–*V*) curve. By maintaining an 18-V driving voltage on the anode side, a flow rate of 1 LPM, and an internal PEMFC temperature of 40 °C and by varying the driving voltage from 10 to 20 V on the cathode (air) side, the *I*–*V* curve was calculated and is shown in Fig. 16. The figure reveals that a higher humidity is not always preferred. The current density can reach a maximum of 840 mA cm^{-2} with a 14-V driving voltage (RH = 81% in Fig. 14) on the cathode side.

Fig. 17 provides the *I*–*V* curve for the PEMFC when the cathode-side driving voltage is maintained at 14 V and the driving voltage on

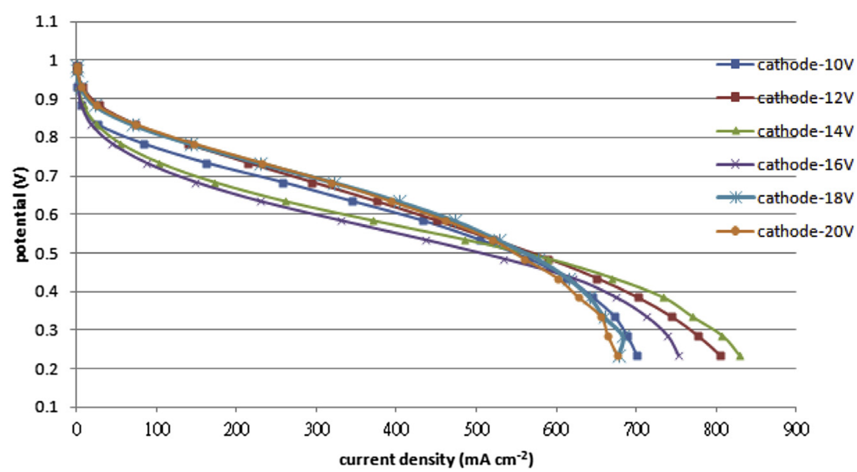

Fig. 16. The *I*–*V* curve of PEMFC for varying cathode (air) side driving voltage. The anode (hydrogen) side driving voltage is fixed at 18 V, flow rate is 1 LPM and the temperature in PEMFC is 40 °C.

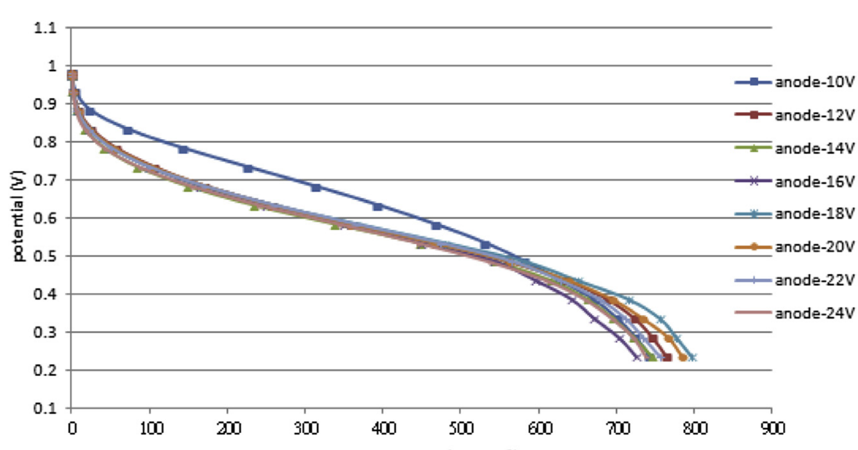

Fig. 17. The *I*–*V* curve of PEMFC for varying anode (hydrogen) side driving voltage. The cathode (air) side driving voltage is fixed at 14 V, flow rate is 1 LPM and the temperature in PEMFC is 40 °C.

the anode (hydrogen) side varies between 10 and 24 V. According to Fig. 15, when the anode-side driving voltage ranges between 10 and 16 V, the humidity is below 75%, and the current density can only reach approximately 720–740 mA cm^{-2}. The current density can reach a maximum of 800 mA cm^{-2} when driven at 18 V (RH = 80% in Fig. 15) and decreases with higher driving voltage due to excess humidification.

4. Conclusions

The ultrasonic atomizer performs better than a bubble-type humidifier. For the bubble-type humidifier, the maximum relative humidities for air and hydrogen are approximately 85% and 83%, respectively, with flow rates from 1 to 25 LPM. To vary the humidity, one must vary the water temperature, but this is relatively undynamic and inefficient, especially at high flow rates when large quantities of water must be heated.

For ultrasonic humidification, the RH values depend upon the driving frequency, the flow rate, the driving voltage, the gas temperature, etc. Two frequencies (1.75 and 2.58 MHz), flow rates from 1 to 24 LPM, driving voltages from 12 to 24 V, and gas temperatures from 60 to 100 °C were investigated in this study. The RH values can reach or exceed 90% for both air and hydrogen given optimal parameter settings.

The RH value can be enhanced by increasing the driving voltage, which indicates that the ultrasonic humidity can be actively controlled to overcome the drawbacks of low RH values at high flow rates and an inefficient control of the humidification using bubble-type humidifiers. Finally, an investigation of a 1-LPM PEMFC also indicated that its performance can be improved by providing the optimal ultrasonic driving voltage.

Acknowledgments

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